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3D GRATING OPTICAL SENSOR HAVING A DIFFUSION GLASS FOR CONDUCTING CHROMATOMETRY WITH COLOR CONSTANCY PERFORMANCE

The invention relates to a grating optical sensor comprising the features of the preamble of claim 1.

Such a sensor is disclosed in WO 97/22 849. It is provided for accurately determining spatial and/or temporal spacings in focused image sequences of a lens/pupil system and/or determining spatial and/or temporal object parameters in real time such as, for example, speed or depth. A 3D grating has also already been used to carry out model calculations relating to the inverted retina of the human eye and to relate them to subjective phenomena known from human vision. In the preferred form, the 3D grating has a hexagonal structure. Other structures with centrosymmetrical diffraction patterns are, however, likewise possible.

Since the investigations of O. Lummer and the industrial development of daylight-like luminaires, it has been realized that there is an as yet unexplained resonance between sunlight and human vision. This has resulted in all the previous recommendations for approximating the spectrum of artificial light sources to the sunlight spectrum. In particular, in the case of color perception in phototopic day vision, there occur in the event of a change of illuminations having a different spectral composition of the radiation

displacements of the color values which are compensated adaptively in human vision after a relatively short or, in part, relatively long time by means of approximate color constancy performances of the eye. The v. Kreis model, which attributes the adaptivity to the visual pigments of the retina, presently serves as an incomplete explanatory model for this. In addition, there are even more incomplete cortical explanatory models from other authors.

On the other hand, it has been documented many times that the phototopic seeing process cannot be characterized solely by the spectral light sensitivity of the individual cones. The very much more complex mode of operation of the visual sense requires knowledge of the luminance distribution in the entire visual field for the purpose of judging many visual tasks. Human vision is not based on the stimulus/ reaction response of individual pixels. It takes account of the relative values over the entire field of view. In addition to chromatic adaptation effects, scattering of light at ocular media influences the extent of the achromatic axis (black-gray-white axis) centering the color space. It is therefore an illusion to believe that spectral photometers will be the ideal instruments of future chromatometry and color determinations, even if they are designed on the detection of overlapping RGB values. Likewise

incomplete is a chromatometric technique which respectively dispenses with determining the triad of brightness/hue/saturation simultaneously and with reference to a entire field of view.

There is thus a growing need to have available in the future color sensors which can measure color values with reference to the spectral sensitivity curves of human vision, and ensure, given adaptation to artificial illuminations, an approximate color constancy corresponding to human vision. It is the object of the invention to create such a sensor.

This object is achieved in the case of a grating optical sensor of the type mentioned at the beginning by means of the characterizing features of the device claim 1 and of the method claim 15. Advantageous developments follow from the features of the associated subclaims.

The invention proceeds from the finding that it is possible, by inserting a diffractive multilayer (3D) grating into the image plane of an imaging lens/pupil system in the near field downstream of the grating (Fresnel/Talbot space; Fourier space or reciprocal grating), to make available three chromatic diffraction orders (RGB triple) with in each case six discrete interference maxima on mutually concentric circles, such as are described in the case of a hexagonal

grating structure by means of the v. Laue equation known from crystal optics.

The v. Laue equation for diffractive space lattices requires for the production of constructive interference maxima the simultaneous satisfaction of the three phase conditions in the equation |1|

$$(\cos\alpha-\cos\alpha^\circ) = h1\ \lambda/gx$$
$$(\cos\beta-\cos\beta^\circ) = h2\ \lambda/gy \qquad |1|$$
$$(\cos\gamma-\cos\gamma^\circ) = h3\ \lambda/gz$$

(h1h2h3 = triple of integral diffraction orders n; α°, β°, γ° = aperture angle of the light cone incident in the 3D grating, relative to x, y, z; α, β, γ = angle of the diffraction orders relative to x, y, z; λ = wavelength; and gx, gy, gz = grating constant in the x-, y-, z-axial direction). Assuming a hexagonal packing of the optically diffracting elements and grating constant dimensions in µm of $gx = 2\lambda111$, $gy = 4\lambda111/\sqrt{3}$, $gz = 4\lambda111$, in equation |2| $\lambda111$ constitutes the wavelength diffracted with maximum transmission into the 111 diffraction order.

$$\lambda h1h2h3 = \lambda111 = \frac{2(\frac{h1}{gx}\cos\alpha^\circ + \frac{h2}{gy}\cos\beta^\circ + \frac{h3}{gz}\alpha s\gamma^\circ)}{\frac{h1^2}{gx^2}+\frac{h2^2}{gy^2}+\frac{h3^2}{gz^2}} \qquad |2|$$

In the case of perpendicular incidence of light ($\alpha^\circ=\beta^\circ=90^\circ$, $\gamma=0^\circ$) a triple of chromatic diffraction

orders results in the visible spectral region (380-780 nm)

λ111 (longest wavelength) RED

λ123 (average wavelength) GREEN

λ122 (shorter wavelength) BLUE

The spectral transmission curves, which are centered relative to one of these λmax in each case, have a Gaussian shape and are determined at their half width by the number of the surface gratings in the z direction that are present in the 3D grating. In the event of incidence of white light, that is to say light of identical energy in all spectral components, [lacuna] the grating inserted into the image plane of the imaging system, given the selection of λ111 = 559 nm, the result is the trichromatism of the diffraction orders at

λ111 RED = 559 nm

λ123 GREEN = 537 nm

λ122 BLUE = 447 nm

There is thus a trichromatic tuning of the 3D grating, which is based on the resonant setting of the grating constants gx and gz to an integral λ111, and in which a trichromatic equilibrium of the brightness values (Patterson amplitudes^2 weights) is produced in the RGB diffraction orders.

In the case of adaptive chromatic retuning of the 3D grating to an illumination other than a white

one, the relation of the RGB λmax (1 : 0.96 : 0.8 or 25 : 24 : 20) is always maintained. $\lambda 111$ as the resonant wavelength determining the triple shifts to shorter $\lambda 111$ wavelengths in the event of change to a blue illumination, and to longer $\lambda 111$ wavelengths in the event of change to a red illumination. The adaptive shift ends with the complete adaptation to the new illumination, that is to say with the resonant finding of a new RGB equilibrium, of the trichromatically additive white standard, which recenters the color space. The actual resonance factor is the phase velocity $n\nu\lambda = c$ (n = refractive index of the medium, ν = frequency of the light, c = speed of the light).

The following new configuration of the sensor design forms the basis for the color constancy performance of the 3D grating optical sensor in the case of adaptation to variable illuminations.

A diffusion glass or one or more light diffusing gratings are incorporated into the pupil plane (aperture space) of the imaging optical system. Their function is to be seen in that they scatter diffusely as incoherent background into the image plane information likewise present at each location in the pupil, spatially the sum of the spectral intensities and local frequency values which are irradiated into the pupil by all objects in the object space and contribute to optical imaging. As a result, each local

image location is supported by the global information on the entire field of view, against which each local pixel must stand out by being differentiated from it, specifically in brightness, hue, saturation etc. However, each item of local information thereby remains relativized in terms of the global background of the entire field of view.

All the lenses, diffusion glasses or gratings are designed such that they are transparent exclusively for electromagnetic radiation in the visible spectrum (380-780 nm) and therefore these delimit an octave of the wavelengths or frequencies with definite absorption edges. This boundary condition is important because thereby spectral brightness values which could come about through variation in the illumination are cut off at these absorption edges.

In the near field downstream of the diffractive 3D grating, the RGB interference maxima (3x6 concentric maxima) assigned to a local pixel are interconnected via photoreceivers set in a constant fashion in terms of their spectral sensitivity to white sunlight (of identical energy in all spectral components) in such a way that a local RGB sum can be formed as a trichromatically additive brightness value by means of an appropriate evaluation. It is possible thereby to differentiate RGB equilibriums and disequilibriums. RGB equilibriums correspond in the object space to visible

colorless surfaces or illuminations (black-gray-white objects). If illuminations are not visible, but can be inferred only via colorless objects or surfaces, they are represented in terms of their spectral characteristic by gray or white surfaces, what are termed mirrors of the illuminations. The image location with RGB equilibrium, which achieves the greatest aggregate brightness, supplies what is termed the white standard, and thereby defines the tip of the achromatic axis centering the color space. Alternatively, the image location whose RGB values most closely approximate an equilibrium takes over this provision of a white standard. This explains that the white standard can be displaced in the trichromatic space.

The design of a diffractive 3D grating optical sensor which provides trichromatic RGB values in three diffraction orders ensures color constancy when there is ensured together with the sudden or gradual change in the illumination in the object space a resonant mechanism, that is to say one that is adaptive to the spectral composition of the illuminations in the 3D grating, which corresponds to a chromatic tuning of the 3D grating. In the case of a white illumination, that is to say an equal-energy spectral composition, corresponding to average sunlight, of the visible light, three grating constants in the xyz-axial direction are tuned to the RED wavelength (559 nm),

[illegible] standing wave formation in the x- and z-axial directions, that is to say resonance in the 3D grating. Identical values, that is to say RGB equilibriums, result thereby under the three Gaussian spectral photopic curves of the photoreceptors (cones in human vision). The white standard is determined via the RGB sum values of the three Gaussian curves, which are centered relative to the wavelengths 559 nm RED/537 nm GREEN/447 nm BLUE.

After a sudden or gradual change in the illumination, a chromatically triggered reconstruction of the grating constants takes place in the diffractive 3D grating. In the case of a displacement of illumination to the longer wavelength region of the spectrum, the white standard in the 3D grating, still tuned to 559 nm RED, suddenly breaks down. If the adaptive mechanism of the shifting of the white standard then acts in the direction of the changed illumination, the grating achieves a new RGB equilibrium in the case of a chromatic tuning to 728 nm RED, for example. The trichromatically additive color space is thereby centered again relative to an achromatic axis, and the colors are correct again, being experienced as correct.

If, by contrast, the illumination is displaced toward the shorter wavelength spectrum, the grating

achieves a new RGB equilibrium, for example in the case of a chromatic tuning to 513 nm RED.

The adaptive process, which leads as a result to a trichromatic restandardization of the color space in a changed white standard, can be described by the already explained v. Laue equation of crystal optics. The actual resonance factor is the phase velocity in the medium. Spectral triggering of the grating constant dimensions corresponds to the coefficient of thermal expansion for the RED wavelength in the RGB triple. It is possible by means of dosed IR, that is to say thermal irradiation in the 3D grating, or by varying the internal pressure in the 3D grating to vary the grating constant dimensions correspondingly. The sensor according to the invention can thereby ensure the color constancy properties of the human vision system.

A color constancy sensor which is represented technically in the form of a 3D grating or preprocessing filter that can resonate with the centroid of the spectral component of a light source or illumination is very important for all applications in which the color of fabrics and materials must be detected, differentiated and classified by the color perception forming the basis of the laws of human vision. This also holds for the relevant judgment of properties of visible objects that are associated with the hue characteristics, whether this be in general

image processing, whether with automatic viewers in robotics or autonomously driving vehicles, indeed even in the case of sensors for the blind. At the same time, such a sensor is able to render color perceptions under artificial light sources predictable and measurable. Since such a 3D grating transforms the physical parameters (intensity and wavelength) into the psychological triad of brightness, hue and saturation, it is also possible to use a sensor to calculate brightness and saturation values of object surfaces.

An exemplary embodiment of the grating optical sensor according to the invention is illustrated diagrammatically in the drawing and described with the aid of the figures, in which:

Figure 1 shows the design of the sensor,

Figure 1a shows the plan view of a centrosymmetrically trichromatic diffraction pattern,

Figure 2 shows the adaptation to a white illumination,

Figure 3 shows the adaptation to a red illumination,

Figure 4 shows the cycle of the operation of adapting to a red illumination,

Figure 5 shows the adaptation to a blue illumination, and

Figure 6 shows the cycle of the operation of adapting to a blue illumination.

The grating optical sensor illustrated schematically in figure 1 includes as lens/pupil system an imaging lens 1. The latter projects a visible object 2, which is illuminated by a radiation source 3 emitting white light, from the object space onto a diffractive 3D grating as modulator 4 with the grating constants gx, gy, gz in the image plane 5. Three chromatic RGB diffraction orders in the diffraction pattern 6 with six concentric maxima (Patterson weights) each result in a known way for each imaged object 2 in the visible spectrum owing to diffraction in the hexagonal 3D grating optical modulator 4, resonance between $\lambda 111$ and the grating constants as well as interference in the near field downstream of the modulator 4. These are illustrated once again in plan view in figure 1a for an object 2 situated on the optical axis 7 of the sensor. In this case, the red (R) diffraction order is situated on the inner ring, the blue (B) on the middle ring, and the green (G) on the outer ring.

Each diffraction order is assigned a photoelectric receiver 8. All the receivers 8 are set to the same spectral sensitivity for a radiation source 3 emitting white sunlight.

Objects situated outside the optical axis 7 supply identical diffraction patterns 6, which can also be interleaved. The resolution of the image depends on

the grating constants of the 3D grating. Each diffraction pattern is assigned a specific object.

A diffusion glass 9 is inserted into the pupil plane of the lens 1 or a plane conjugate thereto. This diffusion glass can advantageously have a diffracting grating structure. Since imaging beams from all the objects in the object space run through each location of the pupil, image information from the entire object space is distributed simultaneously over the image plane via each diffusion center outward from the pupil plane. Consequently, information on the overall image is superimposed on each local image of an object. The diffusion characteristic of the diffusion glass 9 is to be selected such that diffusion takes place as uniformly as possible over the entire image field, and an image of the local object on the background produced by diffusion is maintained.

The spectral transmission of the lens 1, the diffusion glass 9 and the modulator 4 are limited to the visible region of electromagnetic radiation, in particular to the wavelength region of 380-780 nm.

All the receivers 8, assigned to the same diffraction order R, G, B, of a diffraction pattern 6 are interconnected for the purpose of forming a local chromatically additive brightness value 10. The local trichromatically additive brightness values 11 are additionally produced therefrom in a downstream summer.

The local chromatically additive and trichromatically additive brightness values 10, 11 of the diffraction pattern 5, and the corresponding brightness values 10', 11' of other diffraction patterns are fed to a comparison arrangement 12 for the purpose of determining the diffraction pattern with the best agreement between the chromatically additive brightness values 10, 10' and, simultaneously, a maximum trichromatically additive brightness value 11, 11'. The corresponding brightness values of the selected diffraction pattern are led to a white standard forming unit 13 for the purpose of producing a white standard value. The agreement between the three chromatically additive brightness values means that a colorless object detail is involved. The magnitude of the trichromatically additive brightness value specifies an evaluation on the black-gray-white scale.

The chromatically additive brightness values 10, 10' of the individual diffraction patterns can also be fed to a color value forming unit 14. The sum of the three different chromatically additive brightness values that are referred in each case to the white standard signal, for example multiplied by the reciprocal of the white standard, forms the output signal for the local color value. If there is no measured white standard value available, the color

evaluation can also be carried out by forming the ratio with a fictional white standard value.

The process of white standard formation can be checked permanently or in periodic sequence in a variation signaling unit 15. A variation in the illumination leads either only to a change in the trichromatically additive brightness value 11, 11' of the diffraction patterns selected for the white standard, while an RGB equilibrium is maintained. The white standard value is displaced in this case only on the achromatic axis, centering the color space, for black-gray-white objects.

If the variation in the illumination also leads, however, to an RGB disequilibrium in the diffraction pattern determining the white standard, the cause resides in a variation in the spectral composition of the illumination. The variation signaling unit 15 establishes such a variation and controls an adapter 16 which is assigned a thermal radiation source 17. Thermal radiation on the modulator 4 causes variation in its grating constant as a function of the coefficient of thermal expansion until the white standard forming unit 13 displays a new white standard value. This adaptation process corresponds to an inclination of the achromatic axis centering the color space.

Figure 2 firstly illustrates the adaptation to a white illumination with spectral components of approximately the same energy. The intensity of emission is illustrated in the upper diagram as a function of wavelength. A diffractive hexagonal 3D grating in this case supplies three diffraction orders whose Gaussian spectral transmission curves are centered in relation to λ111 = 559 nm (RED), λ123 = 537 nm (GREEN) and λ122 = 447 nm (BLUE). This corresponds to the sensitivity of the cones in human day vision. The Gaussian curves illustrated in the lower diagram can be described by $a^{-1}\exp(-x^2)$, with $x = (\lambda h1h2h3 - \lambda)/n$ and $a = 0.92$ at $n = 55$ for 111RED, $a = 0.88$ at $n = 53$ for 123GREEN, and $a = 0.56$ at $n = 34$ for 122BLUE. The achromatic, that is to say gray to white, objects reproduce the spectral properties of the illumination in the object space to the extent that this itself is invisible. The product of the spectral intensities and spectral Gaussian curves produce identical brightness aggregate values of 33% each in the three diffraction orders. Their RGB equilibrium supplies the white standard, which centers the trichromiatic color space. In the table below, the values of the spectral brightness distribution are summarized in accordance with the Gaussian curves assigned to the diffraction orders, for the case of a white illumination.

Visible Spectrum wavelength (nm)	Spectral intensity of illumination	Spectral brightness values			
		122 BLUE 447 nm	123 GREEN 537 nm	111 RED 559 nm	Sum RGB
400	600	156	1		157
410	625	337	2		339
420	650	612	6	1	619
430	600	830	12	3	845
440	700	1195	29	7	1231
450	850	1508	67	18	1593
460	880	1364	124	37	1525
470	870	991	203	69	1263
480	880	620	319	122	1061
490	820	300	430	185	915
500	840	135	592	289	1016
510	830	49	733	408	1190
520	820	15	844	[illeg.]39	1398
530	850	4	951	[illeg.]00	1655
540	840	1	951	[illeg.]10	1762
550	830		885	[illeg.]78	1763
560	800		749	[illeg.]69	1618
570	800		612	[illeg.]35	1447
580	800		466	[illeg.]52	1218
590	720		297	[illeg.]70	867
600	740		201	[illeg.]61	662
610	730		122	[illeg.]36	458
620	730		70	[illeg.]32	302
630	700		36	[illeg.]44	180
640	700		18	87	105
650	680		8	48	56
660	690		3	26	29
670	700		1	[illeg.]3	14
680	710			6	6
690	650			2	2
700	600			1	1
Sum	23235	8117	8732	[illeg.]48	25297
%	100	32	35	[illeg.]3	100

Figure 3 and figure 4 illustrate the adaptation to an illumination displaced to the red. The intensity of emission is illustrated once again in the upper image as a function of wavelength, and that of the associated Gaussian spectral transmission curves is illustrated in the lower image of figure 3. The 3D grating optical adaptation to a red illumination leads via a chromatic tuning of the three grating constants at $\lambda 111$ = 728 nm RED, $\lambda 123$ = 699 nm GREEN, $\lambda 122$ = 582 nm BLUE to a new trichromatic RGB equilibrium position which is displaced to the longer wavelength end of the spectrum and forms the new white standard. The product of variable spectral energy distribution in the illuminating light and a constant triple of the Gaussian curves results in the new distributions of the spectral brightness values in the RGB diffraction orders, as they are summarized in the following table.

Visible spectrum wavelength (nm)	Spectral intensity of illumination Red (T3)	Spectral brightness values			
		122 BLUE 582 nm	123 GREEN 699 nm	111 RED 728 nm	Sum RGB
490	700	1			1
500	800	4			4
510	820	17			17
520	880	56			56
530	920	158			158
540	950	371			371
550	970	724	1		725
560	950	1138	3		1141
570	1000	1619	5	1	1625
580	1000	1840	7	[illegible]	1850
590	1100	1936	17	[illegible]	1958
600	1200	1698	39	[illegible]	1743
610	1200	1149	77	[illegible]	1239
620	1300	707	151	31	889
630	1300	339	257	61	657
640	1300	137	404	1[illeg.]3	654
650	1400	50	639	2[illeg.]1	900
660	1500	16	935	[illeg.]7	1318
670	1350	3	1071	[illeg.]0	1574
680	1350	1	1269	7[illeg.]0	1980
690	1350		1402	[illeg.]3	2345
700	1350		1440	11[illeg.]3	2613
710	1350		1379	13[illeg.]5	2744
720	1350		1230	14[illeg.]9	2719
730	1350		1021	15[illeg.]9	2540
740	1350		789	14[illeg.]9	2238
750	1350		568	12[illeg.]5	1863
760	1350		381	13[illeg.]4	1465
Sum	32790	11964	13085	1[illeg.]8	37387
%	100	32	35	[illegible]	100

The resonant adaptation operation illustrated in figure 4 starts with a disequilibrium in the RGB diffraction orders at 43% R, 39% G, 18% B, which was initiated by the sudden change from the white to the red illumination. Gradually progressive 3D grating optical resonance with longer λ111 wavelengths finally leads to the chromatic grating constant tuning at

$\lambda111$ = 728 nm RED, and thus to the new RGB equilibrium with 33% R, 35% G and 32% B.

Figure 5 and figure 6 show in a similar way the 3D grating optical adaptation to a blue illumination via a chromatic tuning of the three grating constants at $\lambda111$ = 513 nm RED, $\lambda123$ = 492 nm GREEN, $\lambda122$ = 410 nm BLUE to a new trichromatic RGB equilibrium position, that is displaced to the short-wave end of the spectrum and forms the new white standard. The product of variable spectral energy distribution in the illuminating light and a constant triple of the Gaussian curves results in the new distributions of the spectral brightness values in the RGB diffraction orders, as they are summarized in the following table.

Visible spectrum wavelength (nm)	Spectral intensity of illumination Blue (T 1)	Spectral brightness values			
		122 BLUE 410 nm	123 GREEN 492 nm	111 RED 513 nm	Sum RGB
400	870	1304	47	15	1366
410	900	1481	91	32	1604
420	910	1384	159	62	1605
430	850	1004	241	103	1348
440	810	625	346	164	1135
450	850	360	509	271	1140
460	880	172	688	411	1271
470	800	61	760	513	1334
480	760	18	807	619	1444
490	700	5	795	695	1495
500	620	1	692	693	1386
510	550		561	648	1209
520	500		435	582	1017
530	480		331	516	847
540	460		234	428	662
550	420		147	315	462
560	380		85	216	301
570	340		45	137	182
580	320		24	86	110
590	310		12	51	63
600	300		5	29	34
610	280		2	15	17
620	280		1	8	9
630	250			3	3
640	240			1	1
650	230			1	1
Sum	14280	6415	7017	6614	20046
%	100	32	35	33	100

The resonant adaptation operation illustrated in figure 6 starts with a disequilibrium in the RGB diffraction orders at 24% R, 28% G, 48% B, which was initiated by the sudden change from the white to the blue illumination. Gradually progressive 3D grating optical resonance with shorter λ111 wavelengths finally leads to the chromatic grating constant tuning at λ111 = 513 nm RED, and thus to the new RGB equilibrium

[lacuna] 32% R, 35% G and 33% B.

The resonant adaptation operation also leads, of course, to a geometrical displacement of the position of the diffraction orders in the diffraction pattern, and thus with reference to the photoelectric receivers. However, this displacement always remains within the compass of the extent of the receiver surfaces.